

Hidden Sector Dark Matter and LHC Signatures

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Abstract.

We discuss the implications of a gauged Abelian hidden-sector communicating with the Standard Model (SM) fields via kinetic mixing with the SM hypercharge gauge field, or via the Higgs quartic interaction. We discuss signatures of the hidden-sector gauge boson at the LHC in the four-lepton channel. We show that a hidden-sector fermion can be a natural dark-matter candidate with the correct relic-density, discuss direct-detection prospects, and show how Higgs signatures may be altered at the LHC.

Keywords: Hidden sector gauge symmetry, Higgs boson, LHC phenomenology

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This paper summarises the analysis presented in Refs. [1] and [2] and the reader is referred to these works for more details and a fuller list of references.

The theory: The SM has two gauge invariant, flavor-neutral operators that are relevant (dimension < 4): the hypercharge field-strength tensor $B_{\mu\nu}$ and the SM Higgs mass operator $|\Phi_{SM}|^2$. Hidden sector (i.e., non-SM states with no SM charge) abelian gauge bosons X and Higgs bosons Φ_H can couple to these operators in a gauge invariant, renormalizable manner: $X_{\mu\nu}B^{\mu\nu}$, and $|\Phi_H|^2|\Phi_{SM}|^2$. In this letter we investigate the phenomenological implications of the existence of these two operators.

We consider an extra $U(1)_X$ factor in addition to the SM gauge group. Details are presented in Refs. [1] and [2], and related aspects can also be found in Refs. [3]. We start by exploring the coupling of X_μ via kinetic mixing with B_μ . The kinetic energy terms of the $U(1)_X$ gauge group are $\mathcal{L}_X^{KE} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$, where we take the parameter $\chi \ll 1$ to be consistent with precision electroweak constraints. Hats on fields imply that gauge fields do not have canonically normalized kinetic terms.

We introduce a new Higgs boson Φ_H in addition to the usual SM Higgs boson Φ_{SM} . Under $SU(2)_L \otimes U(1)_Y \otimes U(1)_X$ we take the representations $\Phi_{SM} : (2, 1/2, 0)$ and $\Phi_H : (1, 0, q_X)$, with q_X arbitrary. $U(1)_X$ is broken spontaneously by $\langle \Phi_H \rangle = \xi/\sqrt{2}$, and electroweak symmetry is broken spontaneously as usual by $\langle \Phi_{SM} \rangle = (0, v/\sqrt{2})$. The two real physical Higgs bosons ϕ_{SM} and ϕ_H mix after symmetry breaking, and the mass eigenstates h, H are related to the interaction states ϕ_{SM}, ϕ_H by the sine of the mixing angle denoted as s_h and the cosine as c_h .

X_μ signals via $pp \rightarrow h \rightarrow XX \rightarrow \bar{l}l'\bar{l}'l'$: If the exotic gauge boson is sufficiently light, the lightest Higgs boson decays into a pair of them. The decay of the Higgs boson into two X bosons is through Higgs boson mixing. The X boson will then decay into SM fermions if there is even a tiny amount of kinetic mixing, which we assume to be the

case. We are particularly interested in leptonic final states, and we provide details of how $pp \rightarrow h \rightarrow XX \rightarrow \bar{l}l'\bar{l}'l'$ is possible within this theoretical framework, and to explore the detectability of this channel at the Fermilab Tevatron and CERN LHC.

In presenting results in this section, we will choose $\eta = 10^{-4}$, $\xi = 1$ TeV, and unless mentioned otherwise, take $c_h^2 = 0.5$. For illustration, we choose six benchmark points: Points A – F with $(M_h, M_{Z'})$ values in GeV given by (120, 5) ; (120, 50) ; (150, 5) ; (150, 50) ; (250, 5) ; (250, 50) respectively. For these points we compute the differential distributions, make cuts and find the significance at the Tevatron and LHC. We make use of the narrow width approximation and analyse in succession: $pp \rightarrow h$ followed by $h \rightarrow Z'Z'$ followed by $Z' \rightarrow \ell^+\ell^-$.

A 120 GeV (250 GeV) Higgs boson has total width of ~ 10 MeV (~ 2.1 GeV) when $M_{Z'} = 5$ GeV and $c_h^2 = 0.5$. The Z' coupling to the SM sector is proportional to the tiny η , making the width rather small, but these are the only modes kinematically allowed for the Z' to decay into. The Z' total width for $\eta = 10^{-4}$ is 5.8×10^{-10} , 2.7×10^{-9} , 8.2×10^{-9} and 2.0×10^{-7} GeV for $M_{Z'} = 5, 20, 50$ and 100 GeV respectively.

The gluon fusion process $gg \rightarrow h$ is the largest production channel at the Tevatron ($\sqrt{s} = 1.96$ TeV) and the LHC ($\sqrt{s} = 14$ TeV). For instance, at the Tevatron, NLO $\sigma(gg \rightarrow h) = 0.85$ pb for $M_h = 120$ GeV while the sum of the other channels gives 0.33 pb; the corresponding cross-sections at the LHC are 40.25 pb and 7.7 pb respectively. We include only gluon fusion computed at NLO using HIGLU [4]. We use MadGraph to obtain all matrix elements, and generate event samples using MadEvent [5] with CTEQ6L1 PDF [6].

After applying suitable cuts (see Ref. [1]) to maximise signal while reducing background, we find the following cross-sections for points A – F (in fb): 245, 44, 173, 57, 5.6, 2.2 respectively, with the SM background (VV + hZZ) being 0.02, 0.02, 0.03, 0.03, 1.1, 1.1 respectively. We thus see that the prospect of discovering the X_μ in this channel is excellent at the LHC.

Hidden sector fermions: We add to this theory two vector-like pairs of fermions (ψ, ψ^c) and (χ, χ^c) that carry $U(1)_X$ charges but not any SM gauge quantum numbers. Since there are no fermions charged under both the SM gauge group and $U(1)_X$, there are no mixed anomalies. The vector-like nature makes the $U(1)_X$ anomaly cancellation trivial. We add the Lagrangian terms (written with Weyl spinors)

$$\mathcal{L} \supset -\lambda_s \Phi_H \psi \chi - \lambda'_s \Phi_H^* \psi^c \chi^c - M_\psi \psi^c \psi - M_\chi \chi^c \chi + \text{h.c.} \quad (1)$$

where the fermion covariant derivative terms are not shown, and q_ψ represents the $U(1)_X$ charge of ψ . We assume that the vector-like masses M_ψ and M_χ are around the electroweak scale.

There is an accidental Z_2 symmetry under which $\psi, \psi^c, \chi, \chi^c$ are odd, while Φ_H and all SM fields are even. This ensures the stability of the lightest Z_2 odd fermion, which we will identify as the dark-matter candidate.

In addition to the vector-like masses, $U(1)_X$ breaking by $\langle \Phi_H \rangle = \xi/\sqrt{2}$ implies the Dirac masses $m_D \equiv \lambda_s \xi/\sqrt{2}$ and $m'_D \equiv \lambda'_s \xi/\sqrt{2}$.

We will explore the cosmological, direct-detection and collider implications of the theory we have outlined. We will restrict ourselves to the lightest (and therefore stable) hidden sector fermion (denoted as ψ henceforth). The relevant parameters are: M_ψ, κ_{11}

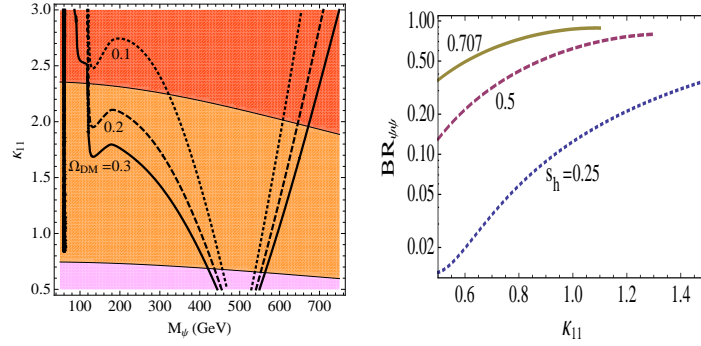


FIGURE 1. Left panel: Contours of $\Omega_{dm0} = 0.1, 0.2, 0.3$ (dot, dash, solid) in the M_ψ - κ_{11} plane. The direct-detection $\psi - N$ cross-section are shown as shaded regions: $\sigma \gtrsim 10^{-43} \text{ cm}^2$ (dark-shade) is already excluded by experiments. $\sigma \gtrsim 10^{-44} \text{ cm}^2$ (medium-shade), and $\sigma \gtrsim 10^{-45} \text{ cm}^2$ (light-shade), the latter two will be probed in upcoming experiments. Right panel: The BR_{inv} as a function of κ_{11} for $m_h = 120 \text{ GeV}$ for $s_h = 0.25, 0.5, 0.707$ (dotted, dashed, solid) with M_ψ adjusted to give the correct dark matter relic density (Ω_0).

(the coupling of the hidden sector fermions to the hidden Higgs), $\kappa_{3\phi}$ (the Higgs cubic coupling), s_h and m_h .

Relic density: $\psi\psi$ annihilations into the W^+W^- , ZZ , hh , $t\bar{t}$ final states will be important if they are kinematically accessible, and if not, the dominant channel is into $b\bar{b}$. We compute the annihilation cross-section in the mass basis including s , t and u -channel graphs.

We show in Fig. 1 (left) the (0.1, 0.2, 0.3) contours of Ω_{dm0} in the M_ψ - κ_{11} plane, with the parameters not varied in the plots fixed at $M_\psi = 200 \text{ GeV}$, $m_h = 120 \text{ GeV}$, $s_h = 0.25$, $\kappa_{11} = 2.0$, $\kappa_{3\phi} = 1$, $m_H = 1 \text{ TeV}$, $\kappa_{H2h} = 1$ and $\xi = 1 \text{ TeV}$. This bench-mark point results in $\Omega_{dm} \approx 0.2$. We see that there exists regions of parameter space that are consistent with the present experimental observations. In the region $m_h > 2M_\psi$, the $h \rightarrow \psi\psi$ decay is allowed, implying an invisibly decaying Higgs at a collider. This connection will be explored in the following.

Direct detection: Many experiments are underway currently to directly detect dark matter, and still more are proposed to improve the sensitivity. In order to ascertain the prospects of directly observing ψ in the $U(1)_X$ framework we are considering, we compute the elastic ψ -nucleon cross-section due to the t -channel exchange of the Higgs boson. To illustrate, for $\kappa_{11} = 2.0$, $s_h = 0.25$, $M_\psi = 200 \text{ GeV}$, $m_h = 120 \text{ GeV}$, we find $\sigma \approx 1.9 \times 10^{-16} \text{ GeV}^{-2} = 7 \times 10^{-44} \text{ cm}^2$. This is very interesting as the presently ongoing experiments [8] are probing this range of cross-sections. With all other parameters fixed as above, as m_h is increased to 350 GeV , the direct-detection cross-section falls smoothly to about 10^{-45} cm^2 . In Fig. 1 (left) we show the direct detection cross-section as shaded regions; from the compilation in Ref. [8], the dark-shaded region ($\sigma \gtrsim 10^{-43} \text{ cm}^2$) is excluded by present bounds from direct detection searches, while the medium-shaded ($\sigma \gtrsim 10^{-44} \text{ cm}^2$) and the light-shaded ($\sigma \gtrsim 10^{-45} \text{ cm}^2$) regions will be probed by upcoming experiments. We have defined our model into the package MicrOMEGAs [7] and checked that our analytical results agree with the full numerical treatment reasonably well.

Higgs Boson Decays: In addition to the usual SM decay modes, if $M_\psi < m_h/2$, the decay $h \rightarrow \psi\bar{\psi}$ is kinematically allowed, leading to an invisible decay mode for the Higgs boson.

We impose the requirement that the relic density should be in the experimentally measured range by scanning over $M_\psi \sim 60$ GeV, and show in Fig. 1 (right) the corresponding BR_{inv} as a function of κ_{11} , with $\kappa_{3\phi} = 1.0$ and $m_H = 1$ TeV held fixed. We see that a significant BR_{inv} is possible while giving the required Ω_0 and being consistent with present direct-detection limits, with the general trend of increasing BR_{inv} for increasing κ_{11} or s_h . Here we have shown only the points that satisfy the direct-detection cross-section $\sigma < 10^{-43} \text{ cm}^2$, to be consistent with current experimental results [8]. For a larger Higgs mass we find qualitatively similar invisible BR with larger values of κ_{11} preferred.

LHC Higgs phenomenology: The discovery significance of the light Higgs in the $gg \rightarrow h \rightarrow \gamma\gamma$, $gg \rightarrow h \rightarrow ZZ \rightarrow 4\ell$ and $gg \rightarrow h \rightarrow WW \rightarrow 2\ell 2\nu$ channels compared to those of a SM Higgs boson with the same mass is reduced appreciably, but we show that the prospects of discovering the Higgs via its invisible decay mode in the vector-boson-fusion channel becomes excellent.

The vector-boson-fusion channel has been analysed in Ref. [9], which we use to obtain significances in the $U(1)_X$ model by multiplying the signal cross-section given there by $BR_{\text{inv}} c_h^2$. The backgrounds included there are QCD and EW Zjj and Wjj . We find in the $U(1)_X$ model after suitable cuts (see Ref. [2]), for $m_h = 120, 200, 300$ GeV, that we need for 5σ significance at the LHC an integrated luminosity of $(0.44, 0.7, 1.3) / (BR_{\text{inv}}^2 c_h^4) \text{ fb}^{-1}$ respectively. For example, for $m_h = 120$ GeV, $BR_{\text{inv}} = 0.75$ and $s_h = 0.5$, we would require a luminosity of 1.4 fb^{-1} for 5σ statistical significance. Alternatively, with 10 fb^{-1} , we can probe BR_{inv} down to about 26 % at 5σ . We thus see that in this channel, the prospect of discovering an invisibly decaying Higgs boson in the $U(1)_X$ scenario is excellent.

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